Chapter 4

Making Sense of the Universe:

Understanding Motion, Energy, and Gravity

4.1 Describing Motion

- Our goals for learning:
- How do we describe motion?
- How is mass different from weight?

How do we describe motion?

Precise definitions to describe motion:

- **Speed**: Rate at which object moves

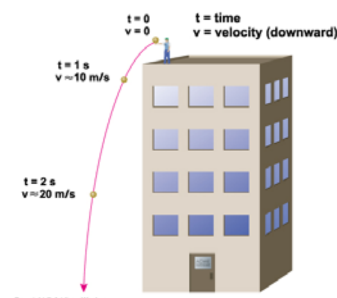
$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}}\right)$$

example: speed of 10 m/s

- **Velocity**: Speed and direction
  example: 10 m/s, due east
- **Acceleration**: Any change in velocity
  units of speed/time (m/s^2)

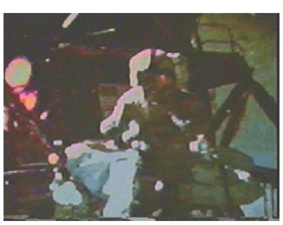
The Acceleration of Gravity

- All falling objects accelerate at the same rate (not counting friction of air resistance).
- On Earth, $g \approx 10$ m/s^2: speed increases 10 m/s with each second of falling.



The Acceleration of Gravity (g)

- Galileo showed that g is the *same* for all falling objects, regardless of their mass.



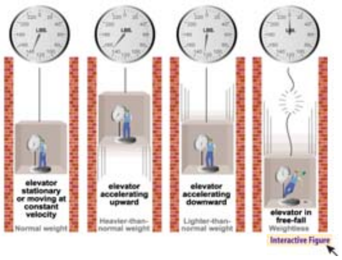
Apollo 15 demonstration

Momentum and Force

- Momentum = mass × velocity
- A **net force** changes momentum, which generally means an acceleration (change in velocity)
- Rotational momentum of a spinning or orbiting object is known as **angular momentum**

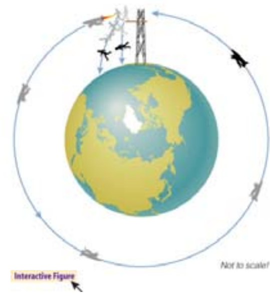
How is mass different from weight?

- **Mass** – the amount of matter in an object
- **Weight** – the *force* that acts upon an object



You are weightless in free-fall!

Why are astronauts weightless in space?



- There *is* gravity in space
- Weightlessness is due to a constant state of free-fall

What have we learned?

- How do we describe motion?
  - Speed = distance / time
  - Speed & direction => **velocity**
  - Change in velocity => **acceleration**
  - **Momentum** = mass x velocity
  - **Force** causes change in momentum, producing acceleration

What have we learned?

- How is mass different from weight?
  - Mass = quantity of matter
  - Weight = force acting on mass
  - Objects are weightless in free-fall

4.2 Newton's Laws of Motion

Our goals for learning:

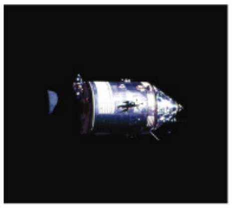
- How did Newton change our view of the universe?
- What are Newton's three laws of motion?

How did Newton change our view of the universe?

Sir Isaac Newton (1642-1727)

- Realized the same physical laws that operate on Earth also operate in the heavens
  - ⇒ one *universe*
- Discovered laws of motion and gravity
- Much more: Experiments with light; first reflecting telescope, calculus…

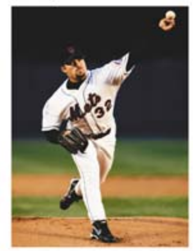
What are Newton's three laws of motion?



Newton's first law of motion: An object moves at constant velocity unless a net force acts to change its speed or direction.

Newton's second law of motion

Force = mass × acceleration



Newton's third law of motion:

For every force, there is always an *equal and opposite* reaction force.

What have we learned?

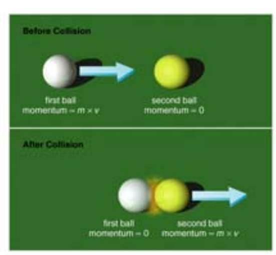
- How did Newton change our view of the universe?
  - He discovered laws of motion & gravitation
  - He realized these same laws of physics were identical in the universe and on Earth
- What are Newton's Three Laws of Motion?
  - 1. Object moves at constant velocity if no net force is acting.
  - 2. Force = mass × acceleration
  - 3. For every force there is an equal and opposite reaction force

4.3 Conservation Laws in Astronomy:

Our goals for learning:

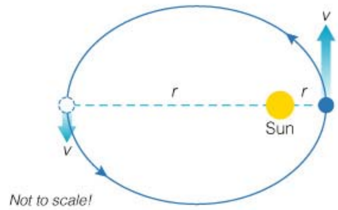
- Why do objects move at constant velocity if no force acts on them?
- What keeps a planet rotating and orbiting the Sun?
- Where do objects get their energy?

Conservation of Momentum



- The total momentum of interacting objects cannot change unless an external force is acting on them
- Interacting objects exchange momentum through equal and opposite forces

What keeps a planet rotating and orbiting the Sun?



Conservation of Angular Momentum

angular momentum = mass x velocity x radius

- The angular momentum of an object cannot change unless an external twisting force (torque) is acting on it
- Earth experiences no twisting force as it orbits the Sun, so its rotation and orbit will continue indefinitely

Angular momentum conservation also explains why objects rotate faster as they shrink in radius:

Where do objects get their energy?

- Energy makes matter move.
- Energy is conserved, but it can:
  - Transfer from one object to another
  - Change in form

Basic Types of Energy

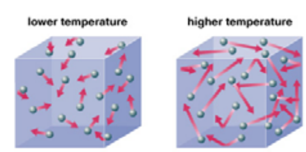
- Kinetic (motion)
- Radiative (light)
- Stored or potential

Energy can change type but cannot be destroyed.

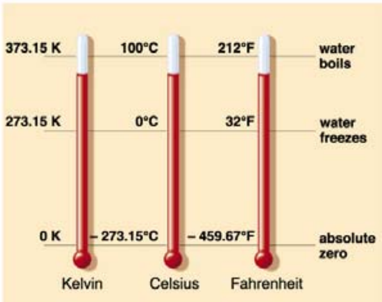
Thermal Energy:

the collective kinetic energy of many particles (for example, in a rock, in air, in water)

Thermal energy is related to temperature but it is NOT the same.
Temperature is the *average* kinetic energy of the many particles in a substance.

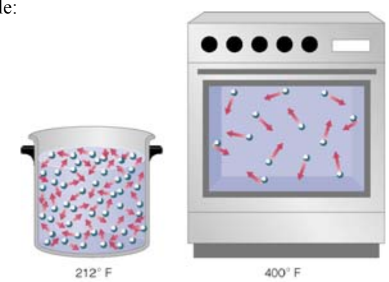


Temperature Scales



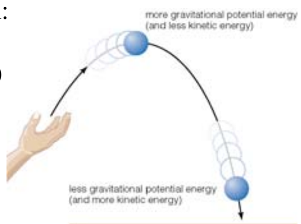
Thermal energy is a measure of the total kinetic energy of all the particles in a substance. It therefore depends both on *temperature* AND *density*

Example:



Gravitational Potential Energy

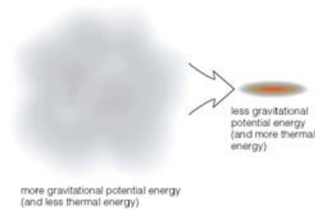
- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (*g*)
  - distance object could potentially fall

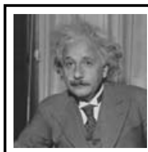


Gravitational Potential Energy

- In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts.

⇒A contracting cloud converts gravitational potential energy to thermal energy.





Mass-Energy

Mass itself is a form of potential energy

$$E = mc^2$$

- A small amount of mass can release a great deal of energy
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators)

Conservation of Energy

- Energy can be neither created nor destroyed.
- It can change form or be exchanged between objects.
- The total energy content of the Universe was determined in the Big Bang and remains the same today.

What have we learned?

- Why do objects move at constant velocity if no force acts on them?
  - Conservation of momentum
- What keeps a planet rotating and orbiting the Sun?
  - Conservation of angular momentum
- Where do objects get their energy?
  - Conservation of energy: energy cannot be created or destroyed but only transformed from one type to another.
  - Energy comes in three basic types: kinetic, potential, radiative.

4.4 The Universal Law of Gravitation

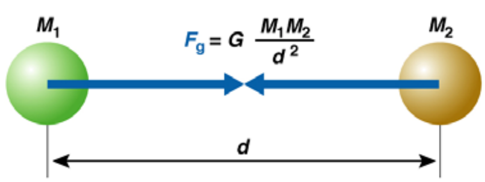
Our goals for learning:

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?

What determines the strength of gravity?

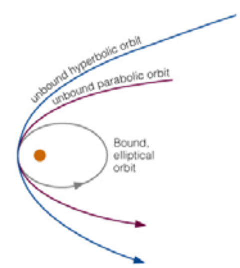
The **Universal Law of Gravitation:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.

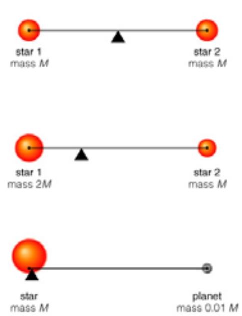


How does Newton's law of gravity extend Kepler's laws?

- Kepler's first two laws apply to all orbiting objects, not just planets
- Ellipses are not the only orbital paths. Orbits can be:
  - Bound (ellipses)
  - Unbound
    - Parabola
    - Hyperbola



Center of Mass



- Because of momentum conservation, orbiting objects orbit around their center of mass

Newton and Kepler's Third Law

His laws of gravity and motion showed that the relationship between the *orbital period* and *average orbital distance* of a system tells us the *total mass* of the system.

Examples:
- Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass.
- Orbital period and distance of a satellite from Earth tell us Earth's mass.
- Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.

Newton's Version of Kepler's Third Law

$$p^2 = \frac{4\pi^2}{G(M_1+M_2)}a^3 \quad \text{OR} \quad M_1+M_2 = \frac{4\pi^2}{G}\frac{a^3}{p^2}$$

p = orbital period

a=average orbital distance (between centers)

$(M_1 + M_2)$ = sum of object masses

What have we learned?

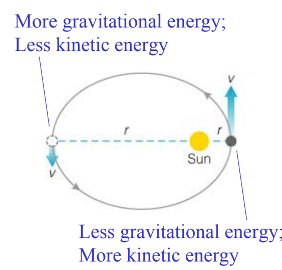
- What determines the strength of gravity?
  - Directly proportional to the *product* of the masses (M x m)
  - *Inversely* proportional to the *square* of the separation
- How does Newton's law of gravity allow us to extend Kepler's laws?
  - Applies to other objects, not just planets.
  - Includes unbound orbit shapes: parabola, hyperbola
  - Can be used to measure mass of orbiting systems.

4.5 Orbits, Tides, and the Acceleration of Gravity

Our goals for learning:

- How do gravity and energy together allow us to understand orbits?
- How does gravity cause tides?
- Why do all objects fall at the same rate?

How do gravity and energy together allow us to understand orbits?



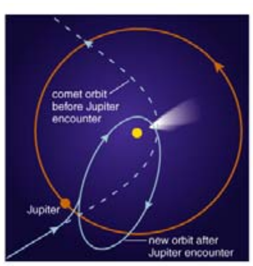
Total orbital energy stays constant

- Total orbital energy (gravitational + kinetic) stays constant if there is no external force
- Orbits cannot change spontaneously.

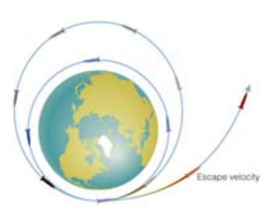
Changing an Orbit

⇒ So what can make an object gain or lose orbital energy?

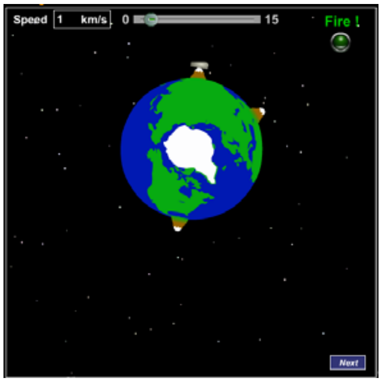
- Friction or atmospheric drag
- A gravitational encounter.



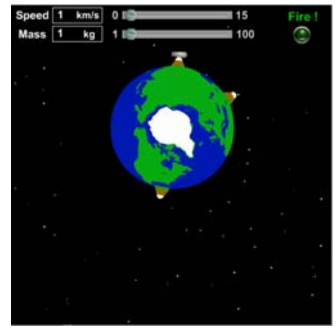
Escape Velocity



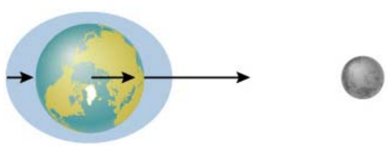
- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit)
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)



Escape and orbital velocities don't depend on the mass of the cannonball



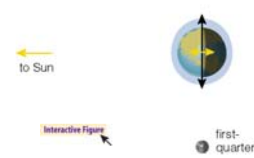
How does gravity cause tides?



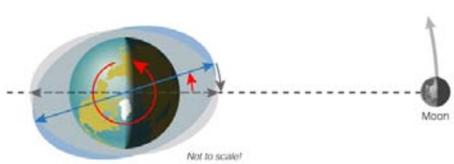
- Moon's gravity pulls harder on near side of Earth than on far side
- Difference in Moon's gravitational pull stretches Earth

Tides and Phases

Size of tides depends on phase of Moon



Tidal Friction



- Tidal friction gradually slows Earth rotation (and makes Moon get farther from Earth).
- Moon once orbited faster (or slower); tidal friction caused it to "lock" in synchronous rotation.

Why do all objects fall at the same rate?

$$a_{\text{rock}} = \frac{F_g}{M_{\text{rock}}} \qquad F_g = G\frac{M_{\text{Earth}} M_{\text{rock}}}{R^2_{\text{Earth}}}$$

$$a_{\text{rock}} = G\frac{M_{\text{Earth}} M_{\text{rock}}}{R^2_{\text{Earth}} M_{\text{rock}}} = G\frac{M_{\text{Earth}}}{R^2_{\text{Earth}}}$$

- The gravitational acceleration of an object like a rock does not depend on its mass because M_{rock} in the equation for acceleration cancels M_{rock} in the equation for gravitational force
- This "coincidence" was not understood until Einstein's general theory of relativity.

What have we learned?

- How do gravity and energy together allow us to understand orbits?
  - Change in total energy is needed to change orbit
  - Add enough energy (escape velocity) and object leaves
- How does gravity cause tides?
  - Moon's gravity stretches Earth and its oceans.
- Why do all objects fall at the same rate?
  - Mass of object in Newton's second law exactly cancels mass in law of gravitation.